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Anaerobic digestion in global bio-energy production: Potential and research challenges

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ABSTRACT

It is clear that renewable resources will play a crucial role in limiting the CO_2 emissions. Energy from biomass and waste is regarded as one of the most dominant future renewable energy sources, since it can provide a continuous power generation. In this regard, the application of anaerobic digestion is emerging spectacularly. This manuscript lists and discusses the main beneficial properties of anaerobic digestion. Different types of biomass and waste are suitable for anaerobic digestion: the organic fraction of municipal solid waste, waste oils and animal fat, energy crops and agricultural waste, manure and sewage sludge. The potential, opportunities and challenges of these biomasses are discussed. Typical biogas yield and points of attention are included. The manuscript concludes with an overview and discussion of the major research trends in anaerobic digestion, including the analysis of microbial community development, the extension of anaerobic digestion models, the development of pre-treatment techniques and upgrading of the biogas produced.

Contents

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1. Introduction

Climate change is undoubtedly the most imminent environmental issue the world is facing today. The rise in global temperature will have certain major effects on ecosystems, wildlife, food chains and eventually human life. There is a general consensus that global warming is due to the large scale anthropogenic emission of greenhouse gases, which are mainly caused by the generation of heat and power. Indeed, still a large fraction of the global energy demand is satisfied through the use of fossil fuels. According to the International Energy Agency (IEA), fossil fuels accounted for up to 81% of the world's primary energy supply in 2007 [1] whereas renewable energy sources only contributed a mere 13%. Although much attention is being paid to the technical and economical development of the implementation of renewable energy sources, fossil fuels will remain the most dominant energy source worldwide, estimated at 77% for the period 2007–2030 [2]. This small decrease in the total share will be largely compensated by the expected 2.5% annual rise in energy demands until 2030. Most of the increase will be realized by a higher consumption of coal, followed by gas and oil [1].

It is clear that renewable resources will play a crucial role in the current CO_2-mitigation policy. In this regard, energy from biomass and waste is seen as one of the most dominant future renewable energy sources, especially since that a continuous power generation from these sources can be guaranteed, unlike other types such as solar energy and wind energy. Waste materials like sewage sludge, manure and crop waste are of specific importance since these sources do not compete with food crops in agricultural land usage. The various technologies that are available for power generation from biomass and waste can be subdivided into thermochemical, biochemical and physicochemical conversion processes. A schematic overview is presented in Fig. 1.

Anaerobic digestion, classified within the biochemical conversion processes, is a robust process and is widely applied. The first industrial scale digesters already date back to the first half of the twentieth century. In recent years, the application of anaerobic digestion for the treatment of organic waste has emerged spectacularly and the amount of anaerobically digested substrate from waste has increased at an annual growth rate of 25% [3]. The attractiveness is due to the various beneficial properties of the process, which will be reviewed in the second part of this paper. In order to illustrate the wide applicability and the potential of anaerobic digestion, an overview of the effectiveness for treating various types of biomass and waste, together with the biogas yield, will be provided. The manuscript will conclude with an outline of the most important domains in future research in anaerobic digestion processes.

2. The benefits of anaerobic digestion

Anaerobic digestion is a microbial conversion method that occurs in an aqueous environment, meaning that biomass sources containing high water levels (even containing less than 40% dry matter) can be processed without any pre-treatment [4]. This is not the case for most other conversion technologies. Combustion, for example, only offers a net positive energy balance if the water content of the biomass or waste is below 60% and even then, most of the energy stored in the biomass is used for evaporation of the contained water. Also, the energetic efficiency of pyrolysis and gasification decreases considerably with high water content, and the presence of water in the produced bio-oil is undesirable [5]. The use of these technologies thus necessitates an energy consuming pre-drying step for wet types of biomass and waste.

The valorization of the produced biogas (consisting of ca. 65% CH_4, 35% CO_2 and trace gases such as H_2S, H_2 and N_2) is energy efficient and environmentally friendly because of the low emission of hazardous pollutants. In most cases, biogas is valorized energetically in a CHP (combined heat and power) installation for the simultaneous generation of heat and electricity. These installations typically offer an electrical efficiency of 33% and a thermal efficiency of 45%. As pointed out by various studies [6], the emissions of volatile organic compounds (VOCs) are very limited since 99% of the volatile compounds are completely oxidized during combustion. This is in contrast to incinerators that suffer from the emission of hazardous compounds like dioxins, and hence require extensive flue gas purification. Alternatively, the biogas can be upgraded to natural gas purity and injected in the natural gas grid [7].

The produced slurry (digestate) is nitrogen rich and can in most cases (depending on the nature of the biomass) be utilized in agriculture as a nutrient fertilizer and/or organic amendment [8]. A more novel application is to transform the digestate into biochar, which can be further employed as soil enhancer or an adsorbent for purification of wastewater or flue gas [9].

Anaerobic digestion is not only feasible in large-scale industrial installations, but can also be applied on a small scale. This observation specifically provides opportunities for anaerobic digestion in developing countries and rural areas, where energy supply is limited or even not available at all. One example is the use of simple biomass and waste digesters in rural areas in India that operate on weed and agricultural residues to provide cooking gas for households [10].

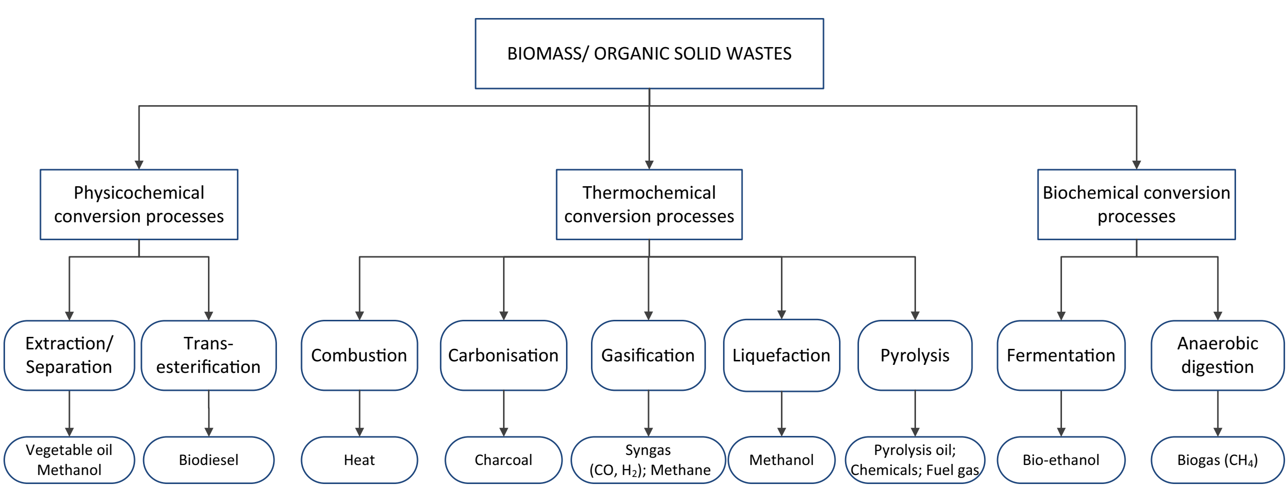

Fig. 1. Biomass and waste conversion technologies.

Finally, some drawbacks of other available technologies make anaerobic digestion even more attractive. Incineration of biomass and waste is still not fully accepted by the public opinion and the formation of gaseous pollutants such as dioxins necessitates the use of an extended gas purification system. Alternative technologies like pyrolysis and gasification are still in demonstration phase and only a limited number of full scale installations has been built. The latter hence does not represent a proven technology.

3. Types of biomass and waste

3.1. Organic fraction of municipal solid waste

The implementation of anaerobic digestion has been one of the major developments in the treatment of municipal solid waste (MSW) during the last decade [11]. Mainly, anaerobic treatment became possible because of the introduction of source separation collection of a clean biodegradable fraction. If MSW is not separated at the source, a pre-sorting step is necessary to remove compounds such as heavy metals not suitable for anaerobic digestion (to obtain a sludge of high quality). This, however, significantly increases the treatment costs.

The composition of this fraction varies greatly: for example, the composition in rural areas will be different from urbanized areas because of a higher fraction of garden waste in a rural area. Also, the composition will undergo seasonal changes, and different locations will infer lifestyle and cultural differences, in terms of both recycling practices and the type of food waste produced [4]. The methane yield, obtained through anaerobic digestion, of various types of MSW (expressed in m^3 methane per kg of organic dry solids (ODS)) was determined by Owens and Chynoweth [12] and is summarized in Table 1.

3.2. Waste oils and animal fat

Considerable amounts of lipid rich waste are produced by the food processing industry, slaughterhouses, the edible oil industry, the dairy products industry and olive oil mills. In all these waste streams, lipids are often the main and most problematic components [13]. At high concentrations, lipids cause different types of problems in anaerobic digesters, including clogging, adsorption to biomass (causing mass transfer problems) and microbial inhibition due to the degradation to and hence presence of long chain fatty acids (LCFA) [14]. Therefore, these materials are always co-digested with other substrate types to reduce the lipid concentration in the digester [15]. Various studies have shown that digesting materials with high-lipid content increases the methane yield [13]. Manure has been identified to be the best co-digesting material to be combined with high fat-containing wastes, because of its high alkalinity, which increases the digester's resistance to acidification due to fatty acid formation [16]. Angelidaki and Ahring [16] observed a 100% increase in methane production when co-digesting manure with 5% olive oil wastewaters and fish oil, where the mixing ratio is usually a function of availability, compared to the methane production of solely manure. The co-digestion of grease and waste oils with manure is a very profitable method for the disposal of household grease, whey or restaurant waste [15].

Table 1
Methane yield, obtained through anaerobic digestion of municipal solid waste (MSW) types.

Type of MSW	Methane yield (m^3/kg ODS)
Mechanically sorted (fresh)	0.22
Mechanically sorted (dried)	0.22
Hand sorted	0.21
Grass	0.21
Leaves	0.12
Branches	0.13
Mixed yard waste	0.14
Office paper	0.37
Corrugated paper	0.28
Printed newspaper	0.10

Adapted from [12].

Table 2
Crop yield and methane yield obtained through anaerobic digestion of various energy crops.

Crop	Crop yield (ton crops/ha)	Methane yield (m^3/kg ODS)
Sugar beet	40–70	0.39–0.41
Fodder beet	80–120	0.40–0.42
Maize	40–60	0.29–0.34
Corn cob mix	10–15	0.35–0.36
Wheat	30–50	0.35–0.38
Triticale	28–33	0.32–0.34
Sorghum	40–80	0.29–0.32
Grass	22–31	0.29–0.32
Red clover	17–25	0.30–0.35
Sunflower	31–42	0.23–0.30
Wheat grain	6–10	0.37–0.40
Rye grain	4–7	0.30–0.41

Adapted from [19].

3.3. Energy crops and agricultural waste

Inedible residues from food crops (e.g. leaves and vegetable wastes) and dedicated energy crops (e.g. maize, beets and wheat) offer a large potential for anaerobic digestion. Ress et al. [18] showed that cellulose can be degraded anaerobically to an extent of about 80%, opening the way to high cellulose containing crops like grasses. Cellulose containing material like straw from wheat, rice and sorghum are widely available as a waste product of food production. Table 2 provides an overview of the typical methane yield obtained through anaerobic digestion of different crops, as well as their production capacity per hectare. These yields can even be improved by co-digestion with other wastes since mixing with other residues provides the necessary nutrients to improve the digester efficiency.

When growing energy crops, a proper choice of the species and variety of the crops is a key factor that determines the methane yield per hectare, together with the time of harvesting, mode of conservation and pre-treatment of the biomass and waste prior to digestion. Maize, sunflower, grass and Sudan grass are the most commonly used energy crops for digestion [17]. It is evident that the crops must be grown in a sustainable way.

The potential methane yield of cellulose-containing materials can in most cases only be realized after pre-treatment because of the high proportion of non-degradable materials present [20]. Diverse pre-treatment techniques such as thermal, chemical, microwave treatments are investigated in the literature, as recently reviewed by Hendriks and Zeeman [21]. Fruit and vegetable wastes on the other hand are degraded very easily and are mostly co-digested with other feedstocks. The methane yield obtained through anaerobic digestion of some common vegetable wastes has been reported by Nallathambi Gunaseelan [22] and is summarized in Table 3.

3.4. Manure

The methane potential of manure comes from the digestion of the organic components present in the faeces and the straw used as bedding material, which mainly consists of carbohydrates, proteins and lipids [23]. Manure is a frequently used feedstock for anaerobic digesters because it is readily available and very suitable

Table 3
Methane yield obtained through anaerobic digestion of fruit and vegetable wastes.

Type of fruit/vegetable waste	Methane yield (m^3/kg ODS)
Mango peels	0.37–0.52
Banana peels	0.24–0.32
Orange peels	0.46
Orange pressings	0.50
Mandarin peels	0.49
Mandarin pressings	0.43
Whole mandarins (rotten)	0.50
Lemon pressings	0.47
Grape pressings	0.28
Pomegranate peels	0.31
Tomatoes (rotten)	0.21–0.38
Onion exterior peels	0.40
Garden beet leaves	0.23
Carrot leaves	0.24
Cabbage leaves	0.31

Adapted from [22].

for the development of anaerobic micro-organisms because of its high nitrogen content. However, the ammonia concentration in some types of manure exceeds the inhibition threshold concentration. Therefore, manure is frequently applied in co-digestion with other wastes that are characterized by low nitrogen concentrations [4]. Manures often contain quantities of organic fibers, including straw bedding material, that are more difficult to degrade than the manure itself [24,43]. An additional motivation for anaerobic digestion of manure is the fact that natural degradation of manure leads to the uncontrolled emission of CH_4 during storage, which is undesirable because of its global warming effects. Controlled anaerobic digestion of manure prevents this uncontrolled release. Moller et al. [23,25] present some values for the methane yield obtained through anaerobic digestion of different kinds of manure. Their results are summarized in Table 4.

Table 4
Methane yield obtained through anaerobic digestion of manure.

Type of manure	Methane yield (m^3/kg ODS)
Pig	0.36
Sow	0.28
Dairy cattle	0.15

Adapted from [23,25].

3.5. Sewage sludge

The disposal of sludge generated during wastewater treatment is a problem of growing importance, representing up to 50% [26] of the current operating costs of a wastewater treatment plant (WWTP). Municipal WWTPs generate sludge as a by-product of the physical, chemical and biological processes used during treatment. Current daily amounts, expressed as dry solids (DS) range from 60 to 90 g of DS per population equivalent (p.e.), i.e. nearly 10 million tons of dry sludge per year for the E.U. [7]. Anaerobic digestion is generally considered to be an economic and environmentally friendly technology for treating these huge amounts of sludge since it has the ability to reduce (by circa 40%) the overall load of biosolids to be disposed [7]. Other beneficial features include the stabilization of the sludge, the improvement of sludge dewaterability, and the potential for inactivating and reducing pathogenic micro-organisms. It is hence increasingly applied to reduce the operating costs of a WWTP. The anaerobic digestion of sewage sludge has the highest biogas production capacity worldwide [27]. The methane yield obtained through anaerobic digestion is very dependent on the sludge composition, however, theoretically, it should be around 0.590 m^3/kg ODS [12].

Fig. 2 summarizes the average methane yield obtained through anaerobic digestion of the different waste streams discussed in this part of the manuscript.

4. Research trends

Although anaerobic digestion is a mature and widely applied technology, the design of digester systems is still generally performed by rule-of-thumb since no tools are currently available for an accurate evaluation of performance [11]. This is mainly due to the fact that the process is not yet fully understood and an optimization of the current technology is still needed. Various fields can be identified in which more research is necessary to further optimize anaerobic digestion processes. These include

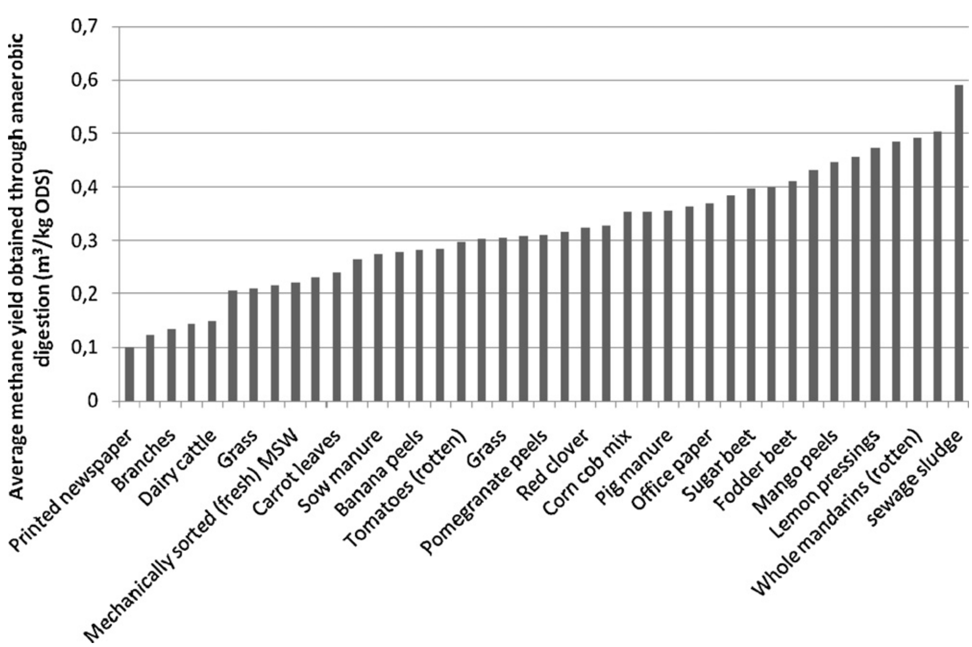

Fig. 2. Overview of the average methane yield obtained through anaerobic digestion of the different waste streams.

(i) the identification of the microbial community dynamics during digestion, (ii) the extension of the existing anaerobic digestion models by inclusion of microbial community data, (iii) the further development and optimization of pre-treatment methods to enhance the anaerobic degradability of the biomass and waste and (iv) the upgrading and purification of the obtained biogas (including its transformation into more value-added components). All these domains will be further discussed in the following paragraphs.

4.1. Identification of microbial community dynamics

Anaerobic digestion is a complex and multi-step microbial process, in which the cooperation between key members of the microbial community is necessary for the optimum performance of the digestion [3]. Some of these communities may contain thousands of interdependent varieties of microbes, many of which cannot be grown under standard laboratory conditions. Within such communities, many functions are accomplished by cooperative efforts among micro-organisms. The complexity of this microbial activity is seen as one of the main reasons for the lack of basic knowledge on digestion systems. Indeed, because of the occurrence of cooperative biochemical pathways, studying one taxon in pure culture is bound to reveal an incomplete insight in the complex biochemistry occurring among partners in the interactive environment of the microbial community, and as most micro-organisms involved cannot be cultivated *in vitro*, the microbial community could only be accurately characterized since the development of culture-independent molecular techniques (reviewed by Talbot et al. [29]).

It is clear that a further development and optimization of anaerobic digestion requires additional fundamental knowledge on the occurring mechanisms on microscale, which should in turn be linked to the macroscale system performance and behavior. Information on the microbial community composition will indeed provide crucial information for the further development and optimization of anaerobic digestion systems [28].

Various studies have already been performed concerning the genetic characterization and/or identification of bacterial and archaeal groups inside anaerobic digesters. For example, Chouari et al. [30] used a combination of 16S ribosomal RNA gene clone library sequencing and dot blot hybridization for assessing the microbial community structures in waste-activated sludge digestion. Shin et al. [31,32] investigated microbial community shifts with food waste-recycling wastewater as a substrate by denaturing gradient gel electrophoresis (DGGE) and real-time PCR. Cirne et al. [33] characterized the microbial communities for a two-stage batch digestion of sugar beets and grass/clover by fluorescence *in situ* hybridization (FISH). The study was able to identify the main bacterial and archaeal groups responsible for the hydrolysis of these substrates. However, the relationship between the dynamic behavior of the microbial communities involved and environmental parameters such as the substrate composition, or process performance has not been fully investigated. Morris et al. [34] stated that the number of methanogens would correlate with methane production rates. They determined the number of gene copies and mRNA transcripts of the methanogen-specific gene mcrA, using a quantitative PCR on DNA and RNA extracted from 4 labscale digesters, operated each under different conditions. They found that the digesters with low methane production rates had fewer copies of mcrA per nanogram DNA and fewer mcrA transcripts per nanogram RNA than the digesters with high production rates. This supports their hypothesis that quantitative PCR can be used to monitor methanogenic activity during anaerobic digestion. The first and (to the best knowledge of the authors) only paper describing research in establishing a relationship between the dynamic behavior of the microbial communities involved and environmental parameters was recently published by Palatsi et al. [35]. These authors studied the influence of successive inhibitory shock pulses of long-chain fatty acids (LCFA) on the metabolic activities and composition of the microbial communities in anaerobic thermophilic digestion. The main objective of this study was, however, to study the adaptation of species and communities to inhibitory components, and no relationship was defined towards system behavior. It is clear that this gap in fundamental knowledge needs to be filled by systematically studying the link between process performance and community development in controlled environmental conditions for different types of digestible biomass and waste.

4.2. Extension of anaerobic digestion models

There is a general agreement in the literature that the application of mathematical models is a prerequisite to improve digester performance and hence much attention is currently focused on the development of accurate models. Various mathematical models have been developed for the description of the anaerobic digestion process, ranging from easy steady-state models to very complex dynamic models, as reviewed by Tomei et al. [36]. The diversity and variety in models developed so far required a convergent action to consolidate the different approaches found in the different existing models. With this objective, the IWA Anaerobic Digestion Model No. 1 (ADM1) was developed by the corresponding IWA Task Group and is described in Batstone et al. [37]. The ADM1 is currently the state-of-the-art and is capable of predicting the major processes occurring in an anaerobic digestion system, and acts as a unified base for modeling of anaerobic digestion [37]. The used nomenclature, units and model structure are consistent with the existing anaerobic modeling literature and the Activated Sludge Models ASM1, ASM2, and ASM3.

Although a large step forward has been made in the descriptive modeling of anaerobic digestion by ADM1, various unsolved issues still remain. For instance, the kinetics involving disintegration and hydrolysis are greatly simplified in ADM1 and most follow-up articles by assuming first order kinetics. The kinetic constant is then determined by calibration and acts as an integration of all complex processes involved in those two steps. This approach is recommended by Batstone et al. [37] as the default method and has been applied by many researchers. However, Batstone et al. [37] acknowledge that the use of surface-based kinetics gives better results, although they argue that results for first order-kinetics are comparable and are similarly good. This is remarkable since in almost all applications of ADM1 the disintegration and hydrolysis parameter results are considered the most important and subjected to calibration by fitting the model to data. The majority of other parameters are assumed constant and assigned a default value, given by the literature or by separate research.

One specific case is the development of accurate models for the anaerobic digestion of solid waste. This topic is even more challenging, as some issues arise that are not dealt with in the existing models, mostly concerning the effects of mixing of the reaction mixture. For instance, Vavilin and Angelidaki [38] have investigated the co-digestion of municipal household solid waste and digested manure in mesophilic conditions. They discovered that in situations where the methanogenic step is rate-limiting, a gentle mixing regime is beneficial for the methane production as in that case spatial methanogenic zones can develop. In case of hydrolysis as rate-limiting step, an intense mixing regime leads to the highest degradation.

Another critical point is the inclusion of microbial community data in digestion models. Models like ADM1 do not distinguish

between micro-organisms performing the same reaction – which implies all of them are assumed to have the same properties – and can therefore not adequately represent or predict experimental results concerning this type of interspecies diversity [39]. Predictions made by current models are therefore only substrate specific. Ramirez and Steyer [40] were the first to present an approach to account for the microbial diversity in complex models such as the ADM1. Their approach considered the improvement of performance of ADM1 when average kinetic parameters were replaced by a set of 10 kinetic parameters, each representing a separate species. The number of species for each group was chosen arbitrary without real knowledge of the underlying community and kinetic parameters were attributed stochastically. One must realize that a full and completely deterministic model is an almost utopic idea because (i) the number of microbial species present in an anaerobic digester culture is very high, (ii) the microbial community evolves dynamically between different levels of activity and (iii) some micro-organisms are not obligatory but facultative anaerobic. Nevertheless, microbial community data will provide very useful information to enhance the predictive power of the models, and furthermore create additional basic insights in anaerobic digestion.

A final problem in modeling this process is the availability of data needed for system identification. The number of independent components found in a digester can be extremely large, and its measurements are often time consuming and costly. Furthermore, only a limited number of process variables can be measured on-line, which makes automated control more difficult.

4.3. Development of pre-treatment methods

The major drawbacks of anaerobic digestion are its long retention times (typical 20–30 days) and low overall degradation efficiency for organic matter, which are partly caused by the inability of the anaerobic micro-organisms to degrade certain biomass components efficiently. The main incentive to apply pre-treatment methods is therefore to alter the substrate composition in such a way that it is more suitable for digestion. Therefore, pre-treatment (disintegration) methods are attracting much attention for their suitability to alter the structure and composition of the biomass and hence enhance the anaerobic digestion. Disintegration (or pre-treatment) techniques are often employed to optimize the biomass-to-energy conversion and thus to bypass the low digestion efficiency that is often encountered in industrial scale applications. Waste sludge from biological wastewater treatment plants is an example, where the organics reduction through digestion is limited to about 50%, even after a residence time of 20 days. The use of pre-treatment methods is particularly useful when digesting lignocellulosic biomass and wooden fractions [21,41]. The lignin, hemicellulotic and cellulotic structures, which form the bulk of the biomass are hardly biodegradable by the anaerobic micro-organisms, resulting in very long retention times and a low digestion output. Disintegration of these structures by pre-treatment allows a more easily and more efficient degradation of the organic matter.

Various disintegration techniques have been implemented and extensively studied in the literature: physical [42], chemical [43–45], biological [33,46] and thermal [47,48] treatment. Also, combinations of the pre-cited methods have been assessed in the literature. Applying a pre-treatment generally leads to an increase of biogas quantity and production rates, energy costs being covered by the additional biogas production [49,50].

Despite the numerous studies and applications of these techniques, both on lab and industrial scale, there is no optimum treatment dosage or intensity available. Most authors use the release of sCOD (soluble part of COD) as a measure for characterizing the efficiency of the treatment. However, no unambiguous relationship between sCOD and anaerobic digestion efficiency could be determined, and a recent paper by Appels et al. [51] presented some indications that sCOD as such is not a good indicator for the biochemical methane production potential of waste activated sludge. It is assumed that the biodegradability and availability of the solubilized organics play a crucial role, since they influence the rate of the hydrolysis step, which is the first step in the digestion and generally considered to be rate limiting for the total anaerobic digestion process. The composition of the sCOD will hence be important and should further be investigated. The obtained results can be used to optimize and apply pre-treatment methods more efficiently.

4.4. Biogas upgrading

The biogas produced by anaerobic digestion is a clean and environmentally friendly fuel, although it contains only about 55–65% of CH_4. Other constituents include 30–40% of CO_2, fractions of water vapor, traces of H_2S and H_2, and possibly other contaminants (e.g. siloxanes). In most circumstances, it can be introduced in power gas engines (preferably in a combined heat and power (CHP) installation) without further purification. However, upgrading is needed for more novel applications like vehicle fuel and fuel cells. If properly upgraded, the biogas can also be introduced in the natural gas grid [7]. The latter applications obviously provide a higher added value to the biogas.

A wide variety of gas purification technologies have been developed, ranging from traditional adsorption processes to cryogenic separation methods (as reviewed by Patterson et al. [52]). Research is specifically focused on the development and optimization of gas membranes [53].

The removal of siloxanes is of specific interest because their presence gives rise to various operational problems through rapid fouling of the gas valorization equipment by crystalline silica (produced by oxidation of siloxanes in the combustion chamber) [54].

Recent research is also focused on the conversion of biogas to organic (high value added chemicals). This is mostly achieved by converting the methane into syngas (mixture of H_2 and CO), and using this gas as a feedstock in organic industry.

5. Conclusions

Anaerobic digestion is a robust process and its application for the treatment of organic waste has been emerging spectacularly with an annual growth rate of 25% during recent years. Its main beneficial properties include (i) its ability to treat high moisture containing biomass, (ii) a very easy conversion into biogas (it is a naturally occurring process), which can be incinerated with a very limited generation of pollutants, and (iii) its robustness and applicability on small scale. Various types of biomass and waste are suitable for anaerobic digestion, and a co-digestion leads in most cases to superior digestion efficiencies. Although frequently used, the digestion mechanism is not yet completely understood because of the high complexity of the process. Assessment of the microbial community composition and evolution during digestion will most probably further elucidate the working mechanisms of the process. A further development of mathematical models is also necessary for optimization of the digestion system. In order to achieve higher conversion ratios and to improve the biogas production, there is a general consensus that pre-treatment methods will be of crucial importance. However, more research is needed to identify their specific effects on biomass structure that enhance gas production. Finally, upgrading of the produced biogas will further broaden its applicability.

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